Planning of Distributed Energy Resources in Singapore

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Abstract— **To aid in the reduction of the dependency on fossil fuels and greenhouse gas emissions that cause poor air quality, migration from internal combustion engine (ICE) vehicles to electric vehicles (EV) is advised. It will also be essential to integrate renewable energy sources (RES) like photovoltaics (PVs), wind, biogas etc. However, there is little progress in Singapore due to the limited EV electric range in affordable EVs and low EV charging availability. Hence, there is a need for EV charging stations (EV CS) implementation to ease anxiety range, without causing adverse effects on existing electric distribution networks. In this paper, siting and sizing of EV CS is done using K-means clustering algorithm on a test feeder with various predicted EV penetration levels applicable to Singapore. Linear approximation on complex plane power flow analysis and cost analysis were implemented to check the practicality of the proposed methodology. The results showed feasibility in the three EV penetration levels of low 10%, medium 30%, and high 50% with AC slow charging. Optimal charging device rating is AC slow 3.3 kW to better meet the potential charging demands of private vehicles in Singapore, which are to be implemented in residential car parking areas.**

Index Terms—**Charging station planning; Electric vehicles; K-means clustering; Unbalanced distribution system; Voronoi diagram**

I. Introduction

According to World Energy Outlook (WEO) 2017 report [1], there is an increasing global oil demand to 2040 due to consumers worldwide still heavily dependent on fossil fuels, as carbon dioxide (CO2) emissions solely from fuel-based transportations rise and will reach as high as emissions from coal-fired power plants. Moreover, S. Shafiee et al. [2] presented, based on previous global oil consumption trends, that the complete depletion of oil may be met between 2045 and 2050. Therefore, migration from petrol and diesel-based vehicles to electric vehicles (EVs) is advised to globally reduce pollutant emissions that cause poor air quality and decrease the increasing rate of oil depletion [3].

In Singapore, usage of EVs for the replacement of internal combustion engine (ICE) have been prioritized during the past decade for less dependency on fossil fuel usage. In addition, EVs hold the advantage in the reduction of direct tailpipe emission and the higher 60% energy efficiency conversion used in motion, compared to the 20% used in ICE [4]. In [5], H. Murveit stated that in contrast to ICE vehicles, the electric motors of EVs are noticeably quieter than gas engines, require little maintenance from the lack of liquid fuel and oil change, and lower brake wear. This improves the overall quality in transportation with the reduction of collective carbon footprint, increased efficiency, and minimization of overall cost. With the rise in penetration of PVs in Singapore and having a target of 1GWp by 2020, it is inevitable to consider the contribution of PVs in the planning of EVs charging stations in the network.

Emphasis of EVs in Singapore is observed in the implementation of BlueSG - a self-service EV car sharing program launched in late 2017, with an aim to provide "an alternative and environmentally-friendly transportation [6]", allowing users to rent and return the EV at any BlueSG charging point. Additionally, Land Transport Authority (LTA) announced a Vehicular Emissions Scheme (VES) which rewards or penalizes cars on its emission levels in early 2018, as to encourage the purchase of low carbon emission cars [7]. Singapore sets its target in the overall reduction of greenhouse gas emissions to 36% below 2005 levels under the 2015 Paris climate change pact by 2030 [9], with 35% of land transport carbon emissions in Singapore are by private vehicles [8]. However, with the unavailability of EV CS and high initial cost of EVs [5], the number of EVs in Singapore is low at only 222 private EVs in comparison to the total of 574,443 private ICE vehicles in 2017 [10]. The low number of EVs is additionally caused by public's skepticism on EV charging capacity and electric range, although typically an EV's driving range per charge is 100 km, whereas an average user in Singapore drives an estimated 55 km per day [11]. Regardless, to ease the public's range anxiety, there is utmost importance in the implementation of EV CS in Singapore. LTA, working alongside Energy Research Institute (ERI@N) of Nanyang Technological University (NTU), had stressed on the availability of charging stations in housing estates, and aims to increase the number of privately-owned EVs with lower charging infrastructure costs for long-term profitability [11]. Therefore, it is essential to create a reasonable EV CS plan on the charging station location and size in Singapore with the provided information from LTA, requirements of Singapore's traffic network layout, along with Singapore's predicted progression towards EVs, as improper deployment may lead to undesirable impacts on EV development.

The charging demands from public, motorists' convenience, charging capacity redundancy, as well as the performance and charging duration of the EV batteries [12], are to be taken into consideration during the planning. Solving the aforementioned issues will benefit from the government's perspective in terms of optimal utilization of electricity, cost minimization, and reduction of tailpipe emissions, whereas

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from consumer's perspective, it further promotes the migration from ICE vehicles to EVs for lower VES charge, easy-to-access charging facilities, as well as meeting the requirements of EV charging demand. All in all, there is a strong requirement in an effective, reasonable charging station planning [13].

In general, there is focus on the minimization of peak load [14,15], further reduction of greenhouse gases [16-18], minimization of cost [14,15,17,18], and reduction of power losses in the distribution system [19], all of which did not consider the optimal number of charging stations required and sited based on consumer location and charging demand. Therefore, as discussed in [20,21], the issue can be computed along with EV CS service radius. However, the aforementioned papers did not consider on the impacts of deployed EV CS on the grid, requiring further verification to solve the complication.

II. Determinating the Number of EV Charging Stations

A. Estimation of EV Population in Singapore's Context

Level 2 AC slow charging device rated 3.3 kW with an estimated maximum charging time of 7.6 hours from zero SOC was used throughout the methodology due to the reasonable impact on electric grid and shorter charging time [22]. One of the main assumptions is that the EVs are to be charged on a pre-existing distribution system, having no requirement in designing a grid model specifically for EV charging. In choosing an appropriate transmission or distribution system for case study, it is important to take into consideration the number of households in the planning region in order to evaluate the total EV charging demand based on calculated population of EVs. Meanwhile, in the placement of EV CS, it is noted in [23] that the EV stations should be placed as close as possible to the buses. The next phase of this work will include PVs as a major energy source in the distribution network.

IEEE 123 radial distribution system was used, with the default 40 kW spot loads represent 78 households, whereas default 20 kW spot loads represent 39 households, assigned based on the average monthly electricity consumption of public households in Singapore of 371 kWh in 2014 [24]. It is noted that although rated power stems from maximum power with time, since there is a lack of data and that this will not cause great impact with increased sample size, average was used. However, as the households are assumed to be clustered in a generalized Singapore high-rise estate, the load representation can be simplified to 1 flat of 39 households and 2 flats of 78 households. The remaining spot loads are either empty lots or other non-residential areas, which has no influence in the determination of EV stations and charging demands in private vehicles. Therefore, the total number of flats used in this study is 122. The aforementioned distribution system is used as representation of a low voltage distribution system in an area in Singapore, regardless of the configured overhead transmission lines in the system. Additional factors, such as fulfilling the requirements of Singapore's traffic network layout and land adaptability, should be taken in consideration. However, for simplification, the two additional factors were ignored for this research, but will be considered in future work.

The estimated number of predicted EV population in the planning region is computed using (1),

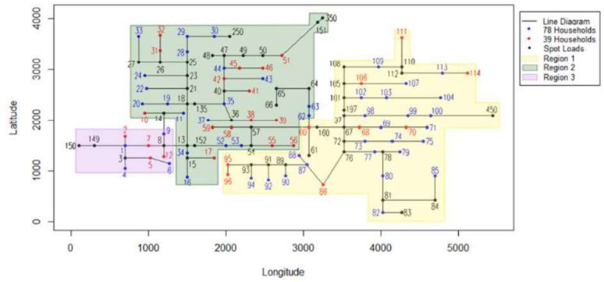

Fig.1. Configuration of 123-bus power system

$$N_{EV} = N_{hh} p N_{vech} \tag{1}$$

whereby the EV penetration levels in Singapore are split into three scenarios - low penetration of 10%, medium penetration of 30%, and high penetration of 50%. According to data in [25], as of year 2017, the number of private vehicles per household in Singapore is considered to be 45%.

B. Charging Demand Prediction

The average electricity demand of an EV per day [20] considers the power consumption of the EV P_{EV}, the average distance travelled d_{avg}, as well as the charge cycles cc per day.

$$P_{avg} = P_{EV} d_{avg} cc_{day} \tag{2}$$

The total electricity demand of EVs P_{demand} in the entire planning region uses (3) which will result in the total electricity demand of low, medium, and high EV penetration levels respectively.

$$P_{demand} = P_{avg} N_{EV} \tag{3}$$

where N_{EV} is the number of EVs.

C. Number of Charging Stations

The number of charging stations N_{CS} is to be calculated using (4), with the average number charging points per charging station was first selected and assumed to be 10. The results were to be rounded to the nearest whole number.

$$N_{CS} = \frac{P_{demand}}{P_{CP} N_{CP} t_{EV}} \tag{4}$$

where N_{CP} is the number of charging points. The multiple scenarios established EV penetration levels in Singapore and the number of charging points per EV CS will affect the number of charging stations chosen. With (4), the number of clusters to be applied in the following k-mean clustering methodology can be determined.

III. Optimal Siting of EV Charging Stations

The methodology in the determination of candidate EV CS sites uses k-means clustering which is ideal for cluster analysis in data mining. The function minimizes distances between the sited residential nodes x_r and the EV CS c which is also the centroid, to find the most optimal solution as shown in (5). As stated previously, the EV CS are to be placed as close as possible to spot loads. However, due to the nature of the algorithm, the 'k' centroids may be placed much further away from the pre-existing nodes of IEEE 123 bus distribution system. To overcome this problem, the ‘k’ centroids were ‘forcibly’ moved to the spot load of the nearest Euclidean distance.

$$min(F) = \sum_{i=1}^{k} \sum_{r=1}^{data} \|x_r - c_i\|^2 \quad (5)$$

$$\sigma(F) = \sum_{r=1}^{data} \|x_r - c_i\|^2 + \sum_{i=1}^{k} \|c_i - \bar{x}\|^2 \quad (6)$$

Quality of the clusters can be accessed by summing up the variations within each cluster. Since k-means clustering is unable to detect the ideal clustering with ‘sight’, the only option is to keep track of the clusters and their total variance σ in (6) and reiterate the process with different starting points until the variance is minimal, resulting in the ideal set of clusters. It is important to note that the number of iterations should increase with an increasing number of clusters. The cluster variation is calculated as the sum of the Euclidean distance between the data points and their respective cluster centroids [26].

After generating the ‘k’ centroid placements and clusters, the xy-coordinates of the centroids are retrieved. The spot loads of nearest Euclidean distance from a centroid can be tabulated, moving the ‘k’ centroids to its new location. K-means clustering algorithm can no longer be applied when the optimal locations of the centroids have been determined and finalized. Voronoi polygon is then applied to determine the service radius and sizing of EV CS, in which the sizing is determined by the number of households within the service area, reusing the equations in (1) to (4) appropriately.

A. *Unbalanced Power Flow Analysis*

The addition of EV CS loads is to respect constraints of power quality and power supply reliability. It is important to take note of nodal voltages and phase angles to prevent from violation. Conventional power flow analysis methods, such as Newton-Raphson method, have limitations on distribution systems due to high R/X ratio from the shortness in line lengths and low voltages [27]. Therefore, linear approximation on complex plane method, based on rectangular formulation, is used in the determination of voltage profile in unbalanced power distribution system. This method proposed by A. Garces [27] had described its accuracy in comparison to conventional back-forward sweep algorithm. The data retrieved in [28] for IEEE 123 node test feeder were compiled, modified and implemented. A linear load flow algorithm is executed for this test case using [29]. It is important to take note of nodal line configurations to prevent load flow analysis errors, as the buses in test network are multi-phasing. The voltage profile constraints from the nominal voltage of IEEE 123 of 4.12 kV are referenced in [30] and [31], whereby the lower acceptable limit of the voltage profile at each bus is 0.9 p.u., and the upper acceptable limit is 1.05 p.u., and the phase angles are to respect the constraints of a three-phase system.

B. *Implementation of Cost Analysis*

The total expenditure can be calculated and evaluated with consideration of placement and sizing of EV CS, as well as the utilized land price. The mathematical models used in [12], are modified to conform with Singapore. In this paper, despite the total line length in the selected distribution system to be around 11 km, to emulate Singapore, the IEEE 123 bus system’s nodes were grouped to represent areas on mainland Singapore, splitting into three regions - Region 1, Region 2, and Region 3. These three areas are essential due to the varying land costs to be accounted into the final minimization of the total production value, with Region 1 representing the suburban pricing, Region 2 representing outlying pricing, and Region 3 representing central pricing. Based on assumption that the percentages of each of the areas taking up the space on mainland Singapore are 50%, 40% and 10%, with 62, 49, and 12 nodes respectively, the IEEE 123 bus nodes are grouped accordingly. Therefore, mathematical model of the objective function on the total expenditure can be formulated as in equation (7), which can be assumed that the EV CS integration takes an estimated time of a year.

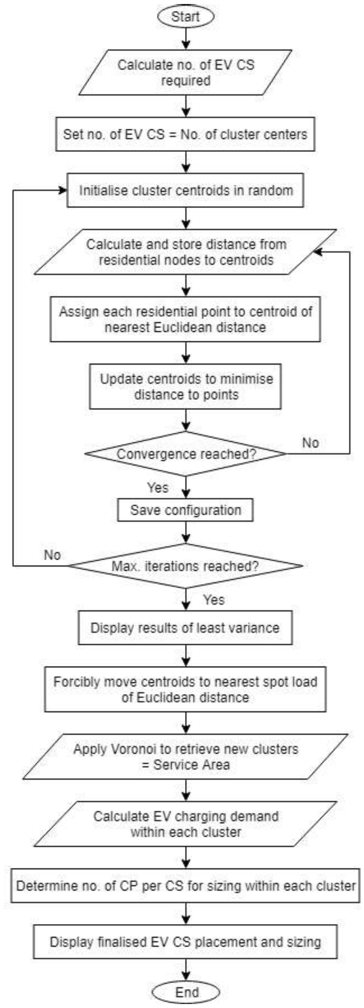

Fig.2. Proposed methodology for siting of EV CS

$$min(f) = \sum_{t=1}^{T} \frac{1}{(1+\eta)^t} \Big[C_{NL}(t) + \sum_{i=1}^{N_{CS}} \Big(C_{CS(i)}^{I}(t) + C_{CS(i)}^{o}(t) + C_{CS(i)}^{M}(t)\Big)\Big] \quad (7)$$

where i and t represents the variable of the i^{th} charging station t^{th}year, j represents the charging point, $N_{CS}$is the number of charging stations, C_{NL} is the loss cost, C^{I}_{CS} is the investment

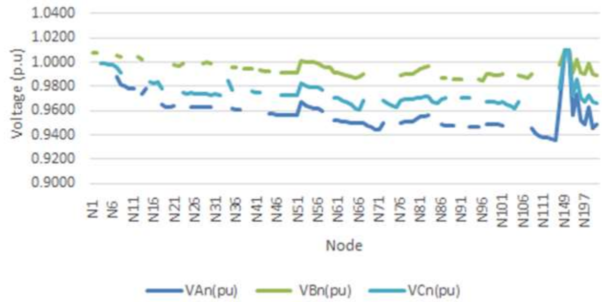

Fig.3. Load Flow for Unmodified IEEE 123 Node Test Feeder

cost, C^{O}_{CS} is the operation cost, and C^{M}_{CS} is the maintenance cost. To complement inflation over the planning period, discount rate to transform future cost to present value is applied as 0.10 [12]. The number of charging stations is dependent on the multiple scenarios in reference to the EV penetration levels in Singapore.

C. Constraints

Constraints are required in reference to the distribution system, and includes both equality and inequality constraints [12]. Equality constraints refer to load flow equations, whereas inequality constraints include capacity limitations for safe operation in the prevention of negative effects on the distribution network.

1) Permitted Load Capacity:

Loads L must not exceed maximum load that bus k can carry.

$$L_k \leq L_{max,k} \tag{8}$$

2) Permitted Nodal Voltage:

Nodal voltage V must not exceed the limits of lower and upper voltages in node k.

$$V_{min,k} \leq V_k \leq V_{max,k} \tag{9}$$

3) Permitted Maximum Transformer Capacity:

Transformer capacity S_{TF} must not exceed maximum transformer capacity of EV CS i.

$$S_{TF(i)} \leq S_{max,TF(i)} \tag{10}$$

4) Permitted Reactive Power:

Reactive power Q_{CS} must not violate the limits of minimum and maximum reactive power in EV CS i for reactive power compensation.

$$Q_{min,CS(i)} \leq Q_{CS(i)} \leq Q_{max,CS(i)} \tag{11}$$

5) Permitted Current:

Current I must not exceed the maximum current of a feeder between k and l.

$$\left|I_{(k)(l)}\right| \leq Q_{max,(k)(l)} \tag{12}$$

6) Permitted EV Charging Power:

Total charging power P_{CS} in all the charging stations and charging points must not exceed the supply capability of the distribution system.

$$\sum_{i=1}^{N_{CS}} P_{CS(i)} \leq P_{CS}^{max} \tag{13}$$

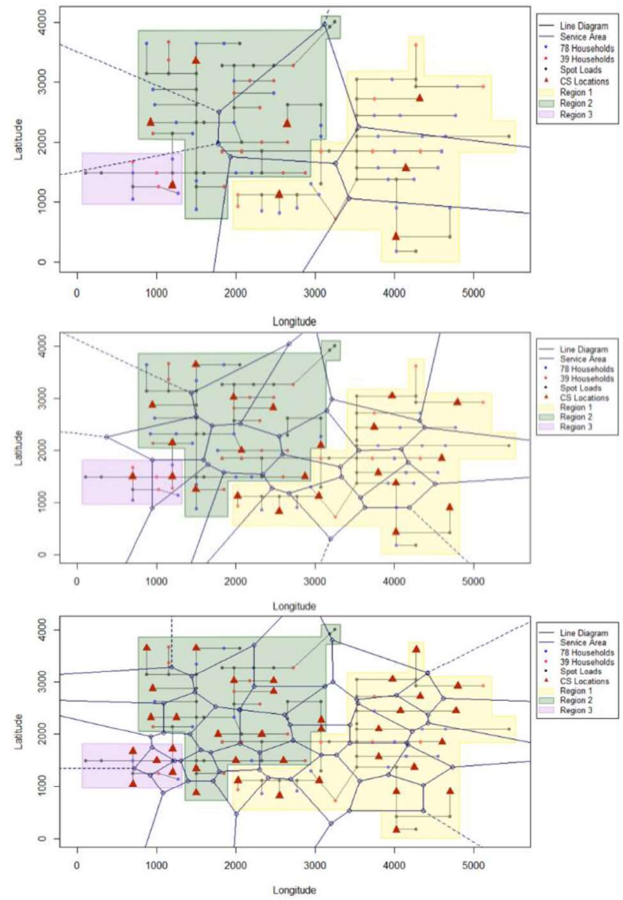

Fig.4. Modified Siting of 10%, 30%, and 50% EV Penetration Levels with 8, 22, and 37 EV CS

IV. SIMULATION & RESULTS

Linear approximation power flow analysis is first used to identify voltage profiles of the default IEEE system. It is observed in Fig. 3. that phases B and C have good voltage profiles between 0.96 p.u. to 1.1 p.u. Meanwhile, although Phase A did not violate the lower voltage limit, it has a higher chance of overloading when extra loads are added in comparison to Phases B and C. It is noted that majority of the nodes are in conjunction to single A-N phase lines. Results showed that Node 114, with a constant power load (PQ) load, is the weakest bus of 0.9357 V p.u., followed by Node 113, a constant impedance (Z) load with 0.9362 V p.u., and finally Node 112, a constant current (I) load with 0.9382 V p.u. All three nodes are in A-N phasing. The linear approximation load flow analysis gives a percentage of error with a maximum of less than 1.7×10^{-3} to prove the reliability of the load flow analysis, and the total power loss in the distribution system with default loads is 98.1758 kW.

A. Location of Charging Stations

The maximum EV CS rated loads, in the scenario where all the EVs are charging during the same time in the planning region, were calculated and equally distributed amongst the EV CS to identify the minimum average number of charging points.

Table 1. EV CS Sizing for 10% EV Penetration Level

Node	Table Column Heading		
	Active Power[1]	*Reactive Power*[2]	*No. of EV CP*
12	57.244	18.21	11
20	41.632	13.68	8
28	46.836	15.39	9
66	52.04	17.1	10
74	67.652	22.23	13
81	20.816	6.84	4
91	62.448	20.52	12
107	57.244	18.21	11

Active power is in maximum kW; Reactive power is in maximum kVAR

Next, k-means clustering is used to identify the EV CS locations in reference to the household density of the location along with the service area of the EV CS. For a 10% EV penetration, the calculated number of EV CS is rounded up to 8, while for 30% EV penetration, it's rounded down to just 22 charging stations, and finally for 50% EV penetration, it's rounded up to 37 charging stations, with all three scenarios having an estimated average of 10 charging points per charging station of a total rated 33 kW. The optimized k-means EV CS locations were then forcibly moved and assigned to the nearest node of Euclidean distance. The coordinates of the new centroids on buses were retrieved, and Voronoi polygon algorithm was applied for the identification of new service areas, simulating the results in Fig. 4.

B. *Sizing of Charging Stations*

With the identification of service areas, the rated real and reactive powers based on the EV charging demand within the service area was determined. EV electricity demand in a service area was first obtained by multiplying the predicted number of EVs within the selected service area in (2), and the average electric consumption of Nissan Leaf per day in (3). The real rated EV power demand within the service area was then achieved by dividing used equation in (3) with AC slow charging time of 7.2 hours [11]. With that, the number of charging points were then computed by dividing the total rated power demand of 3.3 kW, rounding the final answer to the nearest whole number. Finally, the total rated servicing power was found, and reactive power compensation was achieved with 0.95 PF. The aforementioned set of steps resulted in the following sizing and number of charging points for 10% EV penetration level, as an example, to successfully meet the maximum electric charging demand.

C. *Maximum Voltage Profiles*

In all penetration levels, it was noted that the variation for k-means is high due to the density of the households within the area. This may cause voltage drop problems in charging stations with high power ratings within the service area. Unbalanced three-phase linear load flow analysis was then applied in order to affirm the feasibility of both the methodology and all three EV penetration levels onto the distribution system. It is best to measure the maximum voltage profiles as there exists an odd chance in which all the EV charging points are connected, supplying maximum power at the same time to the EVs. Each charging point's maximum power is calculated using the RMS value of 230 V and maximum 16 A rating in AC slow chargers. Results showed that integration of EV CS in all three EV penetration level scenarios and an estimated average of 10 AC slow charging devices per charging scenario is feasible. From the simulated results, the proposed methodology was proven to be a reasonable and satisfactory EV CS plan in the location and sizing assignment of the EV CS within the region with reference to the EV charging demand in a service area. It is observed the overall results in load flow analysis showed that the voltage constraints did not violate the lower limit of 0.9 V p.u. even in the 50% EV penetration level. All in all, the placements and sizing of the EV CS in all three penetration levels have met the overall charging demand and the minimization of distance between residential areas and EV CS.

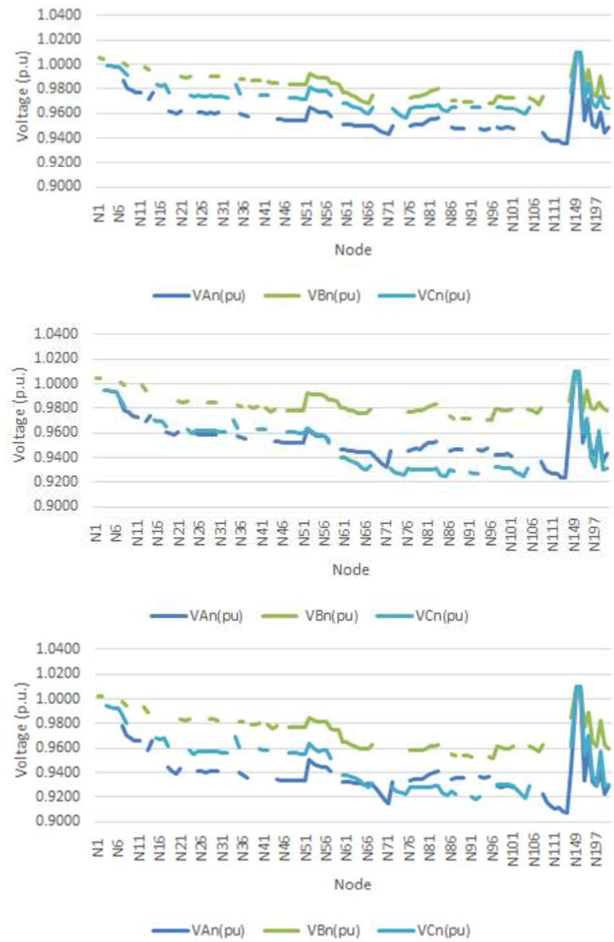

Fig.5. Load Flow for Maximum 10%, 30%, and 50% EV Penetration Levels

Table 2. Total Expenditure of Proposed EV CS Plan

EV Penetration	Cost (S$) in Year 1				
	Network Loss	*Investment*	*Ops*	*Maintenance*	*Total*
10%	162k	155k	1.7M	4707.60	1.85M
30%	208k	450k	4.3M	11.79k	4.54M
50%	344k	734k	7.3M	18.87k	7.62M

D. *Total Cost Analysis*

In 10% EV penetration level of 78 charging points, the average cost is S$23.674k each, followed by 30% scenario of 226 charging points with an average cost of S$20.152k each, and 50% scenario of 368 charging points with an average cost of S$20.706k. Overall, an increased installation of charging points reduces the cost of each charging point as shown from the average price comparison between 10% and 30% of over S$3k difference. Meanwhile, the expenditure cost between 30% and 50% penetration scenarios have minimal difference due 30% penetration scenario having a higher average number of charging points clustered in on EV CS than 50% penetration scenario. This results in a higher average of investment and operational costs in 50% in comparison to 30% EV penetration level. Overall, the cost per charging point is reasonable in comparison to the data collated [32], in which the estimated overall cost for a Level 2 curb-side charging point in the US is estimated to S$12.21k each, excluding operating and maintenance cost.

V. CONCLUSION

The aim of this paper is to propose and develop an effective EV CS plan for private vehicles in Singapore, alongside meeting consumer needs in terms of accessibility to the EV CS and EV charging demand to ease range anxiety. AC slow charging was selected in the integration of EV CS due to its appropriate features ideal in the implementation within residential areas and workplace environments, for the charging of private vehicles. K-means clustering algorithm had successfully identified the EV CS locations, using Voronoi polygon to form the service area of EV CS, and EV CS sizing obtained based on charging demand in each service area. Results showed that k-means clustering algorithm provided satisfactory results in location and EV CS sizing. In addition, the load flow analysis results proved that the additional EV loads at maximum capacity in all three EV penetration scenarios of low 10%, medium 30% and high 50%, can be supported in the IEEE 123 distribution system. The total theoretical raw expenditure in the implementation of the EV CS had been computed and analyzed for comparison, showing that an increase in an average number of charging points per charging station decreases overall costs.

Possible future works include the improvement of the k-means code to improve the cluster initialization of k-centroids, as well as the implementation of G2V and V2G and PVs to further utilize the electricity grid and minimize losses. In addition, an optimization algorithm can be developed and implemented to select which nodal phasing in a k-means selected node with three-phase line configuration is the most ideal for the addition of EV CS loads, further minimizing overall power losses.

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